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Electro-absorption and electro-refraction properties of strained multiple quantum-well structures (QW) in $In_xGa_{1-x}As/GaAs$ were investigated for spatial modulation applications. A new technique that will allow us to obtain large number of quantum well periods and large depth of modulation has been developed. Optical-optical interaction of a modulator-detector diode pair made from such QW structure had been demonstrated. Optimization of QW structure design has been investigated.

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INTERIM ANNUAL TECHNICAL REPORT
RESEARCH ON MATERIALS AND COMPONENTS FOR
OPTO-ELECTRONIC SIGNAL PROCESSING AND COMPUTING

Grant No. AFOSR 84-0389

1. INTRODUCTION AND OVERVIEW

It has been recognized for some time that optical signal processing and optical computing hold considerable promise for high-speed signal processing in DoD applications due to their parallel processing capabilities. In III-V compound semiconductors, optical devices, such as lasers and detectors, have already been realized. Electronic devices such as GaAs MESFET, the InP MISFET and the HEMT have also been demonstrated. Electronic and optical devices could potentially be integrated monolithically on the same chip. However, there are many unresolved issues such as how to obtain efficient modulation and how to integrate different devices on the same chip. substantially more research in materials and components (including microfabrication processing technology) must be undertaken before the full potential of combined opto-electronic signal processing and computing using III-V compound semiconductors can be realized.

For optical computing, spatial light modulators that operate at very high speed and that require very low switching energy are urgently needed. The conventional electro-optical coefficients of III-V compound semiconductors are too small to be useful for efficient spatial modulation. Multiple quantum well (MQW) structures hold great promise for spatial light modulation because they exhibit a strong and sharp exciton absorption. Large electro-absorption (EA) and electro-refraction (ER) effects have been observed due to the quantum confined Stark effect (QCSE) for radiation wavelength near the wavelength of the exciton absorption line. Spatial light modulation utilizing EA has been demonstrated to have very fast response time (100 picoseconds) and low switching voltage (a few volts).

The electronic and optical properties of some semiconductor MQW's can be designed for specific applications by changing the effective thickness of the III-V compound semiconductor layers and the alloy composition of the heterojunction structures which make up such MQW's. Additional flexibility is available in varying these properties and can be obtained by accommodating lattice-mismatched layers by the introduction of uniform layer strains so that no misfit dislocations are generated at the MQW interfaces. Strained layer (SL) MQW's have a lattice constants parallel to the MQW interface, α, which is a strong function of the layer structure, the layer thickness, the

elastic constants and the shear moduli of the alloys [1]. It is, in fact, possible to vary the composition of the MQW and the layer thickness while keeping α fixed and this suggests the possibility of varying, correspondingly, a number of electronic, optical and electro-optic properties, including the fundamental bandgap E_g. The $In_xGa_{1-x}As/GaAs$ SL structure is of particular interest because $In_xGa_{1-x}As$ encompasses a wide range of E_g, from that of InAs, $E_g = 0.36$ eV to that of GaAs, $E_g = 1.42$ eV at room temperatures. It is of interest for spatial light modulator applications because the GaAs substrate used to grow the MQW is transparent for $x > 0$ in the vicinity of E_g of the $In_xGa_{1-x}As$ MQW. In contrast, the GaAs substrate of the $Al_yGa_{1-y}As/GaAs$ MQW structures must be etched away for spatial light modulation in order to avoid substrate attenuation. Moreover the silicon doping of $Al_yGa_{1-y}As$ introduces deep level traps, particularly for $y > 0.2$ and these traps are responsible for the persistent photoconductive effects at low temperatures. These centers may affect the speed of spatial modulation. To first order there seem to be no such problems with the $In_xGa_{1-x}As/GaAs$ system.

$In_xGa_{1-x}As/GaAs$ MQW's using such SL structures were grown by molecular beam epitaxy (MBE) on GaAs substrates by Fritz et al [2,3] with layer thicknesses in the 40Å to 140Å range. A confirmation of the effects of strain and layer thickness of SL $In_xGa_{1-x}As/GaAs$ MQW was provided by Laidig et al. [4] using $x \cong 0.38$ and $x \cong 0.28$. However, they found from X-ray diffraction analysis, a substantial broadening of diffracted peaks of thick layers estimated to be between 770Å and 470Å in thickness, particularly for large values of x, while for layer thicknesses between 96Å and 56Å, the diffraction peaks remain sharp and scanning electron microscopy confirmed, furthermore, that the broadening of the X-ray peaks is accompanied by the presence of structural defects produced by strain relief in the thicker layers.

During the past year, strained layer $In_xGa_{1-x}As$ MQW's were grown at UCSD on n-doped and p-doped (100)-oriented GaAs substrates by means of MBE. The In fraction x was restricted to $x = 0.13$ and $x = 0.15$ thus producing alloy layers with pseudomorphic, tetragonally distorted interfaces. Ten layer MQW's were grown at 530°C on, an initial 0.3 μm thick GaAs undoped buffer layer followed by ten alternating 10 nm thick $In_xGa_{1-x}As$ layers and 15 nm thick GaAs layers with and without a GaAs capping layer. Figure 1 shows a diode made on this structure.

Assuming that the fundamental bandgap at room temperature of the ternary alloy system $In_xGa_{1-x}As$ is represented by

$$E_g = 1.42 - 1.615x + 0.555x^2$$

then for $x = 0.15$, $E_g = 1.19$ eV and $\Delta E_g = 0.23$ eV. By including the correction for the compressive strain on $E_g(In_xGa_{1-x}As)$ we estimate the conduction band discontinuity to be of the order $\Delta E_c = 0.18$ eV and the valence band discontinuity to be $\Delta E_V = 0.05$ eV. In spite of these relatively low band edge discontinuities we have reported the observation of sharp exciton absorption and effective

EA as a function of externally applied bias voltage at room temperature on p-n diodes made of the 10 layers of $In_{0.13}Ga_{0.87}As$ MQW described in the last annual report. We have also reported the large ER effect on a sample supplied to us by the MIT Lincoln Laboratory. These results indicated the large potential of $In_xGa_{1-x}As/GaAs$ QW structures in achieving high speed and low switching voltage spatial light modulation.

For opto-electronic spatial light modulation it is important to obtain large depth of modulation. Hence it is desirable to increase the number of SL quantum well periods by at least a factor of five over the number of periods that we have already made, e.g. 80 to 100 periods. However, recent investigations [5,6] of the critical thickness for single quantum wells with x = 0.28 and strained layer superlattices with 0.14 < x < 0.35 (with an effective strain $\varepsilon = \Delta a/a$ smaller than 2.7%) indicate a strong degradation of heterostructure quality when the total thickness of all the quantum wells approaches the value of the critical thickness L_c, for generating misfit dislocations. L_c has been theoretically derived by Matthews and Blakeslee [7]. These relations were confirmed recently by Anderson et al [8] for the full composition range 0.1 < x < 1.

Clearly there is a need to overcome the inherent limitation posed by L_c if the number of quantum wells for a specific $In_xGa_{1-x}As$ composition to be increased or if the composition is to be changed by increasing x so as to achieve a greater band edge discontinuity. Thus the first major topic currently under investigation is how to accommodate and to limit the dislocations to regions near the substrate interface such that large number of high quality $In_xGa_{1-x}As$ quantum wells can be grown without dislocations.

The second major topic currently under investigation is concerned with the optimization of QW's for modulation. Our first QW electro-absorption device showed that EA can be obtained with $In_xGa_{1-x}As/GaAs$, but there is little doubt that EA and ER can be made larger and more efficient by adjusting the QW parameters such as the well thickness L_z and indium concentration x. The factors important for this optimization have been identified, the dependence of these factors on the electric field and QW parameters has been analyzed and experimental verification has been initiated.

In view of the success that we had in the $In_xGa_{1-x}As/GaAs$ MQW, we proposed in the Amendment of Technical program for the renewal period, December 1986 to January 1988, a research project to develop a simple 2x2 spatial light modulator based on this material system as the third major topic of investigation. A simple hypothetical structure for a single pixel of a future spatial light modulator array was presented in that amendment as sketched in Figure 2. In this case the controlling radiation will be incident from the top side while the signal radiation to be modulated will be incident from the bottom side. The controlling and signal radiations are at the same wavelength. The detector p-n structure may be grown first, followed by the etching of the modulator area and the regrowth of MQW p-i-n structure for the modulator. Alternatively the growth sequence of the detector and modulator may be reversed. The etch and the regrowth of

MQW layers have not been done before and need to be investigated. Both the p-n detector diode and the p-i-n MQW modulator diode are connected electrically in parallel by the metallization pattern to the power supply through a load resistor. The MQW modulator will not sense the controlling radiation because of the metal reflector. The detector will be shielded from the signal radiation by the heavily doped absorber layer. The detector will be designed to absorb the controlling radiation under a wide range of bias voltage. The photo current generated by the controlling radiation through the detector will change the reverse bias voltage applied to the MQW by the voltage drop across the load resistor. Changes in the EA or the ER of the MQW produced by the change in bias voltage will then modulate the reflected signal radiation either in amplitude or in phase. Amplification of the detected signal may be implemented later to increase the sensitivity to the signal radiation, to increase the speed of response and to reduce the effect of the photo current produced in the modulator. Clearly this is a long range and complex project. Thus we have proceeded the investigation in a number of steps. The first step is to demonstrate the basic interaction between the diode and the modulator.

2. RESEARCH PROGRESS

2.1. Investigation of Material Growth Technique for Obtaining a Large Number of Strained QW Layers

Bedair et al [9] have shown a method for reducing the density of threading dislocations originating at the GaAs epitaxial interfaces. They found that strained superlattice structures grown by MBE directly on the GaAs substrate tend to localize the dislocation network and reduce the etch pit count by nearly two orders of magnitude. We have initiated work on the ternary alloy $In_xAl_{1-x}As$ grown on GaAs for different purposes, concerned mainly with application of MODFET structures. We have been interested in the use of an $In_xAl_{1-x}As$ buffer layer to reduce the dislocation densities of the MQW layers. With reference to Figure 3 note that for each $In_xGa_{1-x}As$ alloy there is a corresponding $In_xAl_{1-x}As$ alloy whose lattice constants match. The problem is that of the mismatch between this pair of ternary alloys and their GaAs substrate. We first proposed that by the use of appropriate compositionally graded or superlattice buffer layers between the MQW's and the substrate we would be able to confine the misfit dislocations to the substrate/buffer interface - or at least to the buffer itself so that the MQW's would look at an essentially strain free interface. An attempt to explore the potential advantage of a heterojunction buffer layer was made by growing, by means of MBE, a 0.5 µm thick nominally $In_{0.3}Al_{0.7}As$ layer on a (100) - oriented GaAs substrate upon which were deposited sequentially ten QW's of $In_{0.3}Ga_{0.7}As/In_{0.3}Al_{0.7}As$ (each of ~ 100Å thick, based on an assumed growth rate of 130 Å/min itself based on earlier calibration). Note that these compositions were well in excess of the theoretical limits for pseudomorphic growth.

Transmission electron microscopic observation of the MQW's as well as of the buffer/substrate interface were encouraging although far from ideal. Relatively little buckling was observed in the quantum wells compared to earlier attempts using $In_{0.25}Ga_{0.75}As/GaAs$ MQW's discussed in the last annual report. For most of the 10 μm regions examined the quantum wells were flat from the buffer to the cap layer. There were a large number of micro twins originating primarily at the buffer/substrate interface extending through the MQW's to the surface. A few instances of bulging of intermediate layers were found as well as some dislocation loops. The density of the dislocations appear to decrease from the buffer/substrate interface towards and through the MQW's. This result encouraged us to try a second experiment using essentially the same flux ratios except for a 1 μm thick $In_{0.3}Al_{0.7}As$ buffer layer. The transmission electron micrographs indicated a substantial reduction in the density of defects present in the MQW's; however, dislocation loops were still present, and some dislocations propagated through the MQW's. It becomes clear that increasing the thickness of the buffer layer is not going to solve, by itself, the problem of reducing the density of propagating defects or confining them within the buffer layer. On the other hand, we were also encouraged by the recent reports that the strained quantum wells themselves or a thin section of strained superlattice near the substrate may be used to take up the mismatch of the lattice constants by generating sufficient number of misfit dislocations in the superlattice near the substrate interface, without propagating the dislocations through the MQW's. Thus samples MBE -473, MBE-474 and MBE-476 were grown. MBE-473 consists of 80 periods of 100Å thick $In_{0.15}Ga_{0.85}As$ QW's with 100Å thick GaAs barriers grown on GaAs, MBE-474 consists of 80 periods of 100Å $In_{0.19}Ga_{0.81}As$ QW's with 100Å GaAs barriers grown on GaAs, while MBE-476 consists of 125 periods of 20Å $In_{0.15}Ga_{0.85}As$/20Å GaAs superlattice on 1000Å GaAs buffer, followed by 50 periods of 100Å $In_{0.15}Ga_{0.85}As$/100Å GaAs MQW, then followed by 5 periods of superlattice cap. Figure 4(a), 4(b) and 4(c) show the photoluminescence (PL) spectra of MBE-473, MBE-474 and MBE-476. Figure 5(a), 5(b) and 5(c) show the corresponding transmission spectra of the same samples. The exciton lines are marked by the arrow in these figures. From these results we have clearly succeeded in obtaining good quality QW's. Fifty percent absorption of the transmitted radiation was measured for the 50 periods of MQW in sample MBE-476. The percentage of absorption per well is as good as that of the 10 MQW structure grown earlier. The narrowest PL linewidth is obtained from sample MBE-476, which has a thin superlattice buffer layer to take up the mismatch between the substrate and the MQW layers. The slight discrepancy between the PL and absorption wavelength shown in the two figures may be caused by the inaccurate calibration of the monochromator used for the absorption measurement. Transmission electron microscopy on these samples has not yet been obtained to show us the dislocation distribution pattern. Notice also that the exciton of the MBE-474 is already at the 1.03 μm wavelength. This implies that we are very close in obtaining a material structure that can be used effectively for modulation of the 1.06 μm

wavelength Nd/YAG laser radiation.

2.2. Automation of the MBE Growth by Means of Computer Control

In order to increase the total number of QW layers and to obtain superlattice structures we embarked on the design and construction of a controller such as that shown schematically in Figure 6. It is relatively inexpensive, has now been completed and tested and will be the subject of a paper or note to be submitted for publication in the near future.

It consists of a microcomputer, (in our case) an Apple Macintosh connected to a programmable scanner (in our case) a Keithley Model 705 which has an IEEE 488 compatible interface. The scanner allows the selection of any one or any combination of eight single pole switches that operate the eight available effusion cell furnaces of the MBE reactor. The microcomputer is programmed to select the primary address, dwell time, control intervals of the switch combinations required to operate the MBE. In view of the fact the Macintosh has a serial RS-232C output an I/O interface has had to be introduced to make it compatible with the IEEE-488 input to the scanner (in our case) a Mac 488A bus controller made by I/O Tech. The scanner output is connected to an electronic solid state relay system designed and built at UCSD in accordance with AIE Standard RS-422-A specification. Each solid state relay acts as a shunt switch across the manual switches provided by the console of the MBE reactor which operates the pneumatic shutters. The relay controller can thus be operated either in the manual or computer-controlled mode with appropriate time delays introduced as needed to achieve near steady-state epitaxial growth.

Initial results obtained with this system were highly satisfactory. Successful growth of the samples MBE 473, MBE 474 and MBE 476 are the best evidence that the automated system is functioning properly.

2.3. Quantum Well Optimization

The EA spectrum of a QW consists essentially of a sharp peak, a plateau on the high-energy side of the peak and no absorption on the low-energy side. The peak corresponds to exciton absorption, and the plateau corresponds to continuum absorption. When an electric field is applied perpendicular to the QW's, both the exciton peak and the associated continuum shift to lower energy, lose strength, and are broadened. If the incident light is tuned to the wavelength of the exciton peak in the absence of the electric field, then the absorption of the structure is reduced, and negative EA is obtained. If the incident light is tuned to the wavelength of the field-shifted exciton peak, then the electric field increases the absorption, and positive EA results. Both positive and negative EA may be useful for electro-optic modulation.

The effective absorption coefficient for a QW structure, α_{eff}, is equal to the absorption coefficient in the QW, α, weighted by the factor $L_z/(L_z + L_b)$ where L_b is the thickness of the barrier layer. The absorption coefficient is in turn proportional to the oscillator strength per unit volume, f, which has been studied theoretically and experimentally [10,11]. For large L_z, f is nearly constant and approaches its bulk value. As L_z decreases, f slowly increases, then increases as $1/L_z$ in the intermediate range, and increases more rapidly than $1/L_z$ for small L_z. Thus the absorption per unit length at the exciton peak is larger for narrower QW's. For very narrow QW's, however, the barriers between wells are much thicker than the wells, so the absorption of the combined well/barrier structure does not approach infinity, but approaches a finite limit. The theory cited above treats an infinitely deep QW; for a finite QW the exciton wavefunction extends into the barrier when the well becomes very thin, so the oscillator strength may actually peak for some small but non-zero value of L_z.

The exciton wavefunction in an infinitely deep QW in an electric field has been discussed by Bastard, et al. [12]. They discuss a variational technique for calculating the wavefunction, and they calculate the Stark shift of the exciton peak, which for small electric field can be expressed

$$\Delta E = -(1/6 - 1/\pi^2)^2 \, (m_e + m_h)/(2h^2) \, e^2 F^2 L_z^4.$$

We have used the same wavefunctions to calculate the electron-hole overlap

$$I = |<\Psi_e | \Psi_h>|^2$$

which is in turn proportional to the oscillator strength. In the limit of small electric field the change of the overlap is

$$\Delta I = -(1/6 - 1/\pi^2)^3 \, (m_e + m_h)^2/(2h^4) e^2 F^2 L_z^6.$$

For efficient EA we want to shift the exciton peak by an energy about equal to the full width half maximum (FWHM) of the peak. The ratio

$$\Delta I/\Delta E = (1/6 - 1/\pi^2)(m_2 + m_h)/h^2 L_z^2$$

shows that when the Stark shift is equal to the FWHM, the decrease of oscillator strength is much larger for a wider QW.

For both positive and negative EA wider QW's give the required Stark shift with a smaller applied voltage. A wider QW also gives a larger decay of the oscillator strength, which is desirable for negative EA but not for positive EA.

The literature contains more accurate models for the calculation of EA[13,14], but the model described above qualitatively but lucidly describes the effect of QW thickness on EA characteristics. It shows that when the QW thickness L_z is varied there is a trade-off between large oscillator strength and large sensitivity to the electric field.

The models described above are for infinitely deep QW models, so they do not consider the effect of the QW depth. In practical QW's this may be an important factor, especially in the InGaAs/GaAs material system, since the wells are relatively shallow. Bastard et al.[15] used a finite QW model to predict that the L_z^4 dependence of the Stark shift is partially offset for small L_z, even for relatively deep GaAs/AlGaAs QW's. This model can easily be used to calculate how the oscillator strength depends on L_z for InGaAs/GaAs QW's.

Experimental testing of these principles has been initiated but is not yet complete. Three structures were fabricated which all have ten $In_{0.12}Ga_{0.88}As$ QW's, but with different values of L_z, nominally 50Å, 70Å, and 100Å. For the 50Å structure the exciton peak was too close to the GaAs absorption edge and was obscured by the absorption tail of the GaAs substrate. The other two samples, however, clearly show sharp absorption peaks. The EA spectra, shown in Figure 7 verify that the thinner QW shows a slower peak shift and a much smaller decay of the oscillator strength. The peak strengths are about the same in both cases, which is consistent with the prediction that $\alpha \propto 1/L_z$. Further EA measurements will be made on samples with deeper QW's, to test the effect of QW depth. So far samples with $In_xGa_{1-x}As$ QW's and GaAs barriers, with $x = 0.15$ and $x = 0.19$, have been grown, but EA measurements have not yet been made.

The factors determining the linewidth of a QW exciton absorption line in the absence of an electric field have been reviewed in the literature [16]. The electric field dependence of the linewidth is much less well understood. An applied electric field could cause the carriers to tunnel from one QW to the next, decreasing the exciton lifetime and consequently increasing the linewidth, but the predicted increase of linewidth from this mechanism is much less than the observed increase[17]. It has been suggested, but not confirmed, that field inhomogeneity could contribute significantly to the broadening [17]. If the QW's and barriers contain any unintentional dopant atoms, then there will be an electric field gradient perpendicular to the QW's. If these atoms are ionized by the electric field, then a radial electric field will arise centered on the impurity atom. These field inhomogeneities would cause the exciton energy to be inhomogeneous.

2.4. Demonstration of the Optical-Optical Interaction in a MQW Detector-modulator Diode Pair

As a first step toward the realization of a 2 x 2 MQW spatial light modulator array, we have fabricated two diodes on a SL MQW sample (MBE-322) that contains 10 periods of $85Å In_{0.12}Ga_{0.88}As/100Å GaAs$ with 3000Å of n GaAs buffer and cap layers. The diode electrode consists of a Cr/Au 3.4 mm × 3.4 mm square with a 2 mm window to pass through the light. An experiment is performed to demonstrate the optical-optical interaction as shown in Figure 8. The two diodes are connected electrically in parallel and biased to $V_R = 2.4$ Volt through a load resistor $R_L = 5.1$ K Ω. The diode on the left hand side is used as a detector for the He-Ne laser radiation at

$\lambda = 6328.8\text{Å}$ The diode on the right hand side is used as the modulator for the radiation generated by the tunable pulsed dye laser-parametric oscillator. Since the diodes contain only 10 QW's, a two-detector method is used to measure the modulation effect on the modulator diode. The radiation from the tunable dye laser-parametric oscillator is split into two paths. The signal path goes through the modulator diode to a detector; the reference path goes through a p^+ GaAs sample, that has the same thickness and doping as the p^+ GaAs substrate of the diode sample, to another detector. The output signals from both detectors are sent to the microcomputer for obtaining the difference of the outputs and for averaging out the pulse to pulse variation of the pulsed dye laser-parametric oscillator. The experiment was planned originally for the Argon laser pumped CW dye laser. However since the delivery of that unit is delayed by the manufacturer, a He-Ne laser is used in its place. Since the He-Ne laser radiation is absorbed by the n GaAs cap layer of the detector-diode, the responsivity and the quantum efficiency of the detector-diode are very low. Nevertheless the turning on and off of the He-Ne radiation produced a 1.4 V drop across the load resistor. Both positive and negative EA have been observed in the modulator diode. Figure 9 shows the negative log transmission at $\lambda = 9580\text{Å}$ as a function of V_R. Figure 10 shows the - log transmission of the modulator diode as a function of wavelength. Clearly the best negative EA is obtained at $\lambda = 9580\text{Å}$ and the best positive EA is obtained at $\lambda = 9640\text{Å}$ At $\lambda = 9580\text{Å}$ and at $V_R = 2.4$ V, a 6.8% negative EA modulation is observed when the He-Ne radiation is turned on. At $\lambda = 9640\text{Å}$ and at $V_R = 2.4$ V, a 3.4% positive EA modulation is observed. The percentage of EA modulation observed is consistent with the data we have reported on sample MBE-110 last year.

Clearly we have successfully solved some of the fabrication problems of diodes on MQW samples, and we have demonstrated the optical-optical interaction in a MQW detector-modulator diode pair. A number of issues need to be investigated and resolved before a unit cell such as that shown in Figure 2 can be realized. These issues include: (1) The fabrication of diodes on MQW structures that have superlattice cap and buffer. (2) The technology of etch and regrowth. (3) The effect of optical absorption in the modulator diode on the performance of the modulator-detector pair. (4) The implementing of amplification for the detector current. In addition results obtained in the research of optimizing the material structure for best EA and the use of ER must be incorporated. For example, the use of ER and the use of Fabry-Perot resonance to enhance EA and ER may reduce significantly the optical self-absorption in the modulator diode. We are also considering the demonstration of a coupled-SEED nonlinear element using our $In_x Ga_{1-x} As/GaAs$ MQW structure.

3. SUMMARY

Substantial progress were made in this contract period. The most significant accomplishment is the successful growth of large number of periods of high quality SL QW on GaAs that showed narrow exciton line. If such exciton line could also be designed for modulation of 1.06 μm wavelengths Nd/YAG laser radiation, we would have made a very important advancement. We expect to follow the research direction already outlined in our Amendment to AFOSR during the next contract period.

4. PAPERS PRESENTED PUBLISHED AND SUBMITTED DURING THE CONTRACT PERIOD

1   T.E. Van Eck and W.S.C. Chang, "Electrorefraction and electroabsorption in InGaAs/GaAs multiple-quantum-well structures", paper presented at the Conference on Lasers and Electro-Optics, April 16 - May 1, 1987, Baltimore, MD.

2.   William S.C. Chang "Research in Materials and Components for Opto-electronic Signal Processing and Computing" paper presented at the DARPA/DSO Review Meeting, Feb. 1-13, 1987, Xerox Training Center, Leesberg, VA.

3   William S.C. Chang and T.E. Van Eck "Optic Waveguides and Electro-optical Devices in Heterojunction and Quantum Well Structures of III-V Compound Semiconductors, A Review" Invited talk at the SPIE O-E/Fibers Symposium, Aug. 16-21, 1987, San Diego, CA.

4   C.L. Lin, P. Chu, A.L. Kellner and H.H. Wieder " Composition dependence of Au-$In_x Al_{1-x} As$ Schottky barrier heights", Applied Physics Letters, vol 49, 1593.(1986).

5   P. Chu, C.H. Lin, A.L. Kellner, W.S.C. Chang and H.H. Wieder "Molecular Beam Synthesis and Properties of $In_x Al_{1-x} As$ Strained Layers", presented at International Conference on Superlattices and Microstructures, Chicago, August (1987).

6   H.H. Wieder, "Strained Layer Heterojunction Structures for High Frequency Applications" in DARPA Technical Document 1079 "EHF Monolithic Materials and Devices", May 1987.

5. PERSONNEL SERVED ON THIS CONTRACT

1. Timothy E. Van Eck is a graduate student who is primarily concerned with the research on the optimization of QW structure for EA and ER modulation. He should be completing his Ph.D. Thesis within 6 month time.

2. Shigern Nikki is a graduate student who has automated the MBE system, who is doing the growth of MBE samples and who is fabricating and measuring the detector-modulator pair.

3. C. C. Sun is a graduate student whose research is concerned with gate controlled photo-diode. As a result of the amendment submitted for this contract, that work has been gradually phased out of this contract. Ha has not been supported on this contract since June 1987. Nevertheless, his Ph.D. Thesis is expected within a year. Since his work is no longer of interest to this contract, his work has not been included in this report.

4. Andrew Williams is a new graduate student who just joined us.

5. Peter Chu and Albert Kellner are two graduate students who worked on the material growth and photo-luminescence measurement, but who have not been supported on this contract.

6. The faculty supervisors for this contract are: H. H. Wieder and W. S. C. Chang

6. REFERENCES

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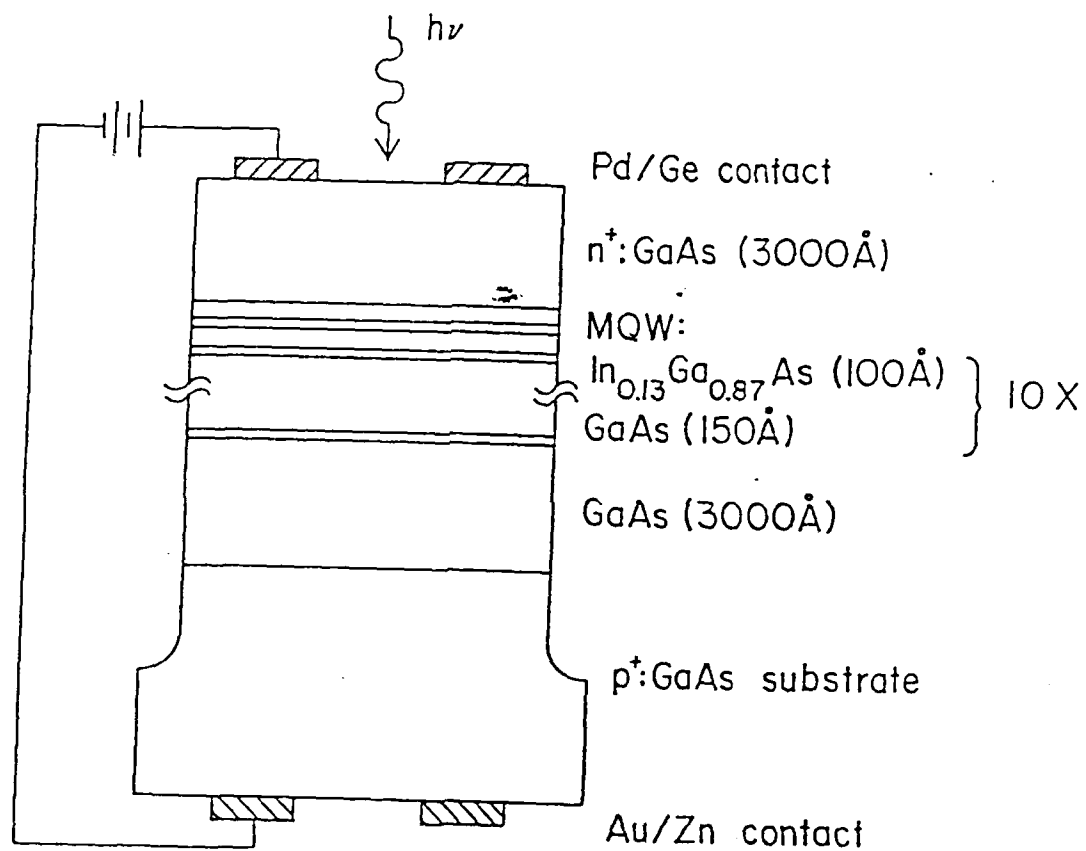
Figure 1. The $In_{0.13}Ga_{0.87}As/GaAs$ diode made at UCSD
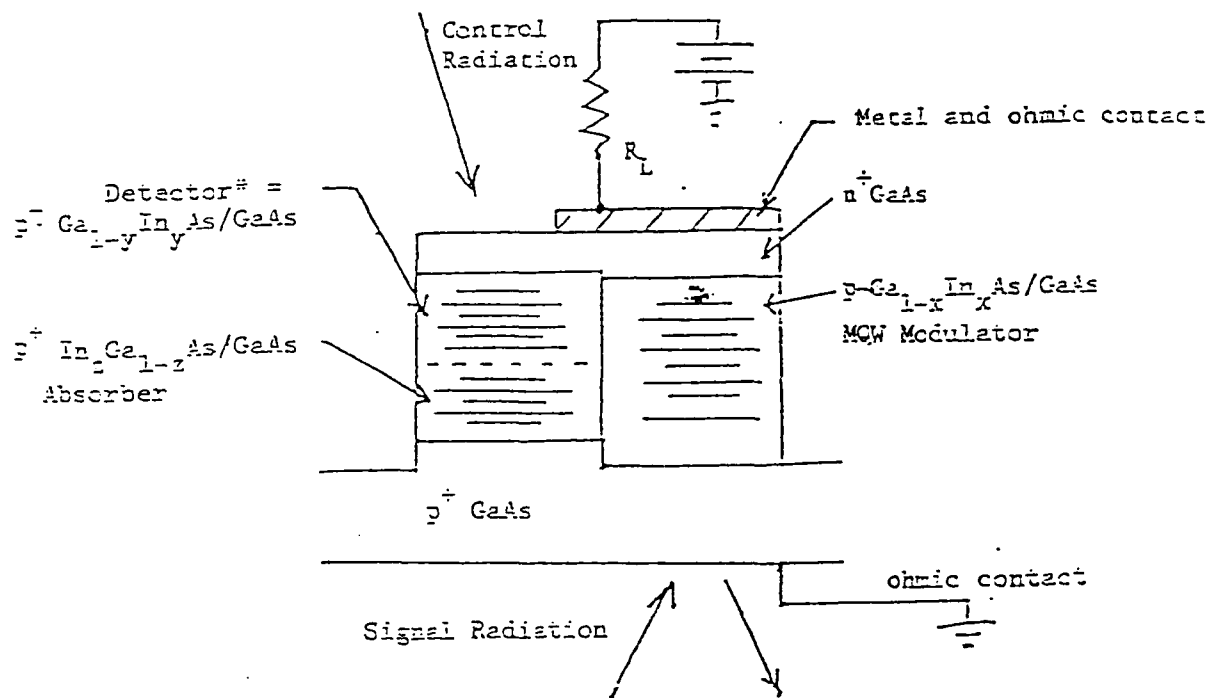
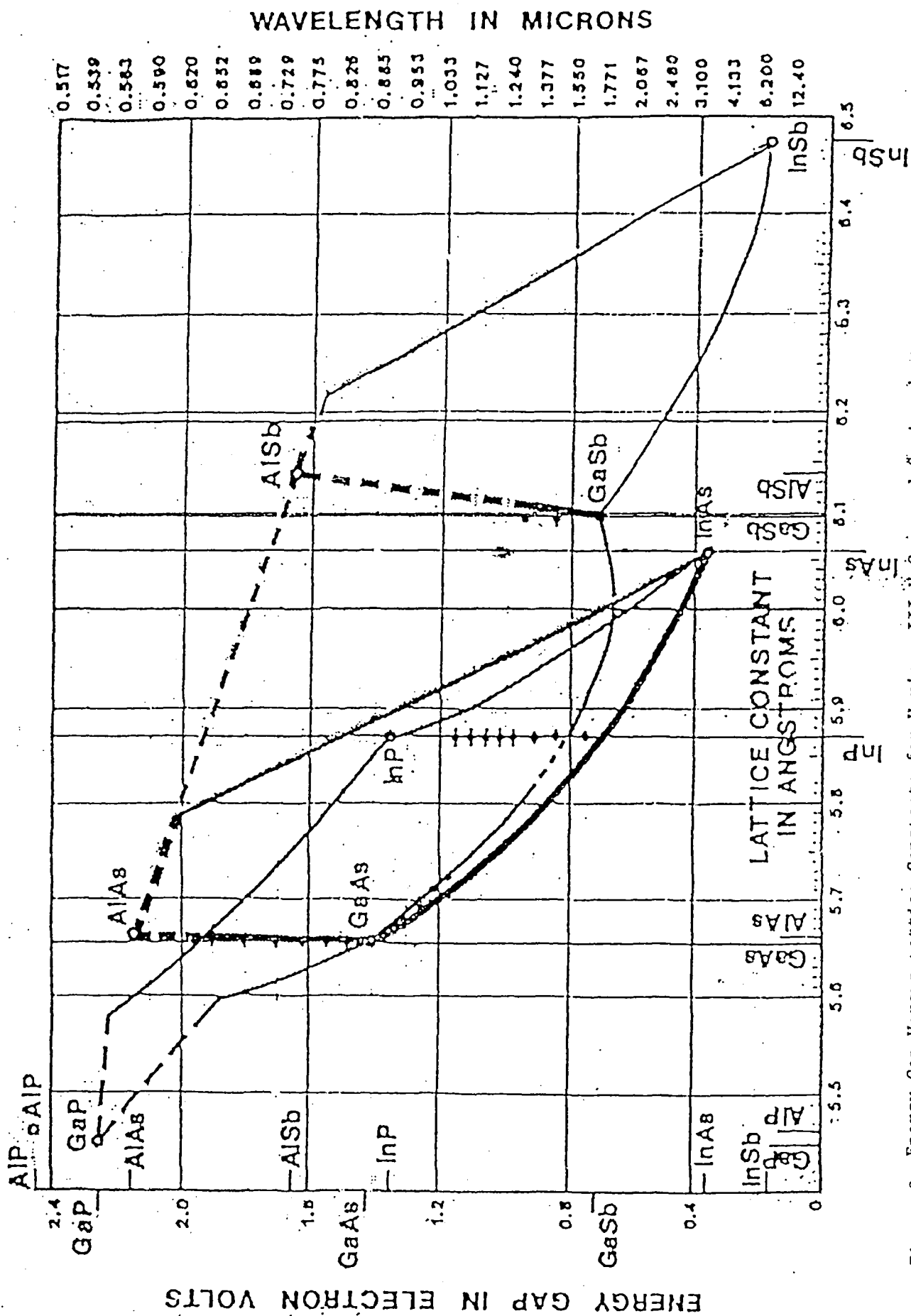Fig. 2 A proposed scheme for a unit cell of a InGaAs/GaAs MQW spatial
light modulator.

Figure 3. Energy Gap Versus Lattice Constants for Various III-V Compound Semiconductors.
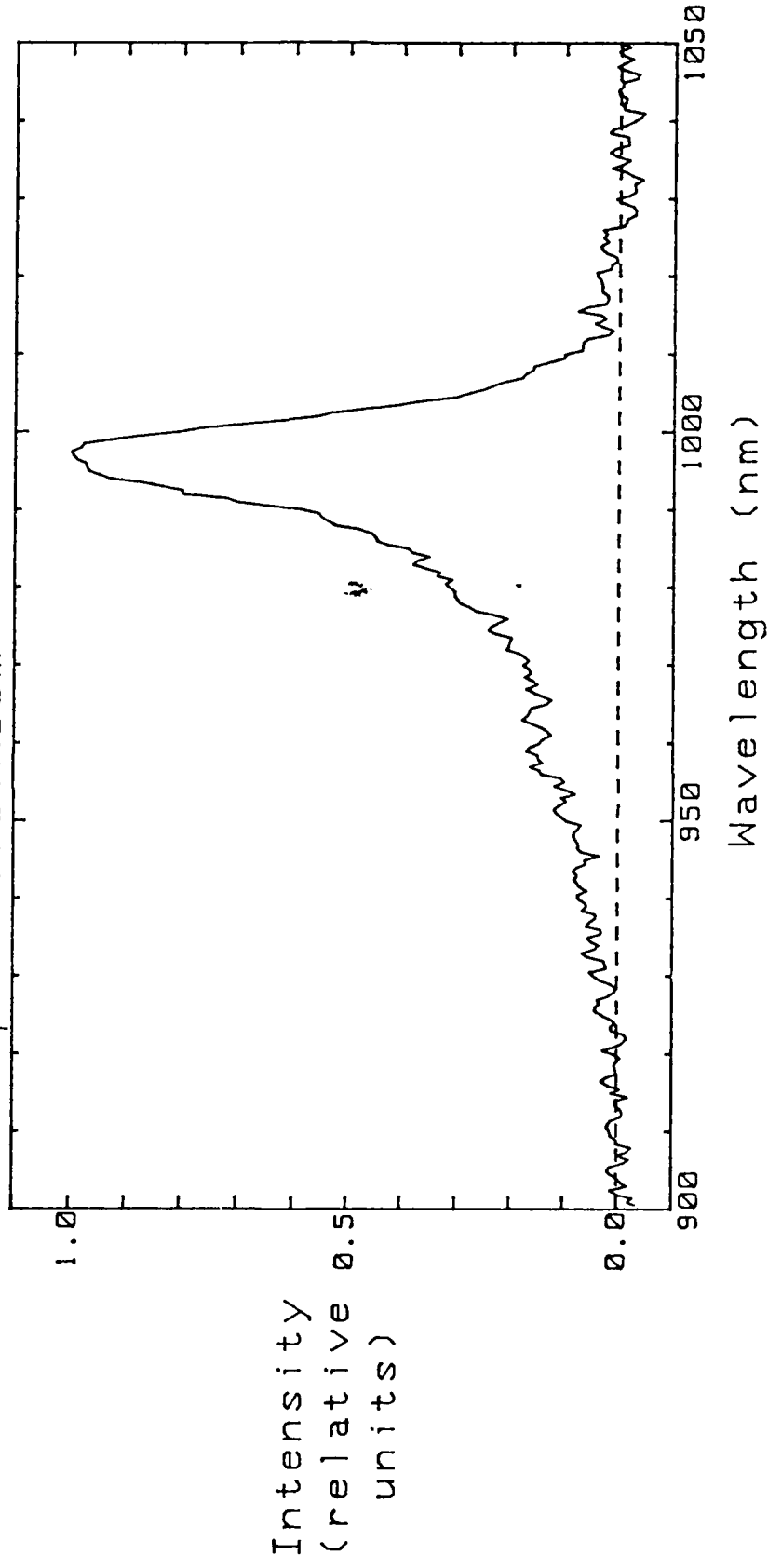
PL Run:092187.05
Sample:MBE473-2
Temperature:Room

Intensity (relative units) vs Wavelength (nm)

Figure 4(a).   Photoluminescence spectra of 80 periods of $In_{.15}Ga_{.85}As/GaAs$ MQW on

GaAs substrate

PL Run:092187.09
Sample:MBE474-2
Temperature:Room

Intensity (relative units)

1.0

0.5

0.0

Wavelength (nm)

900   950   1000   1050   1100
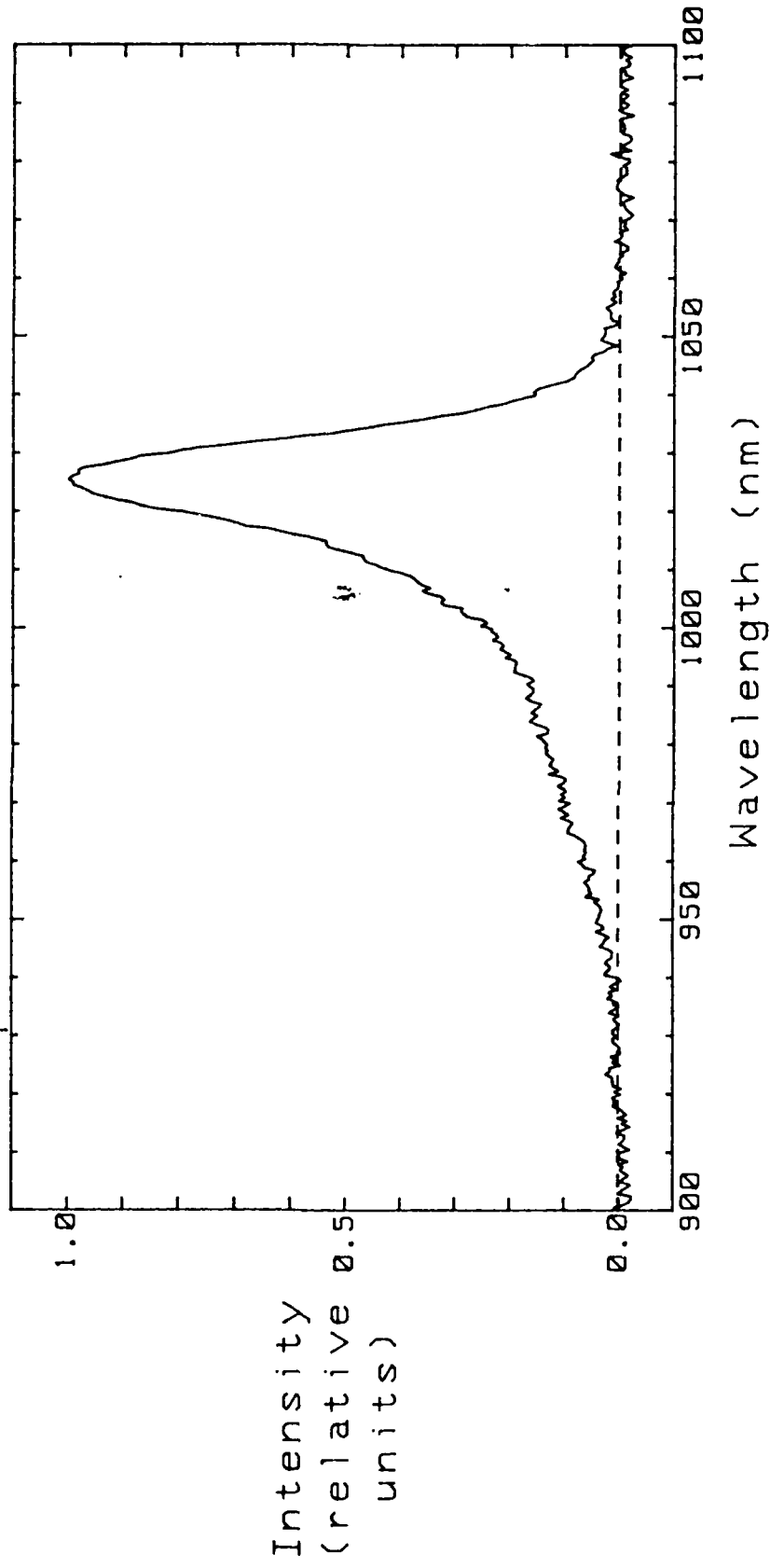
Figure 4(b). Photoluminescence spectra of 80 periods of In.19Ga.81As/GaAs MQW on GaAs

PL Run:092287.02
Sample:MBE476-2
Temperature:Room

Intensity (relative units)

1.0

0.5

0.0

900   950   1000   1050

Wavelength (nm)
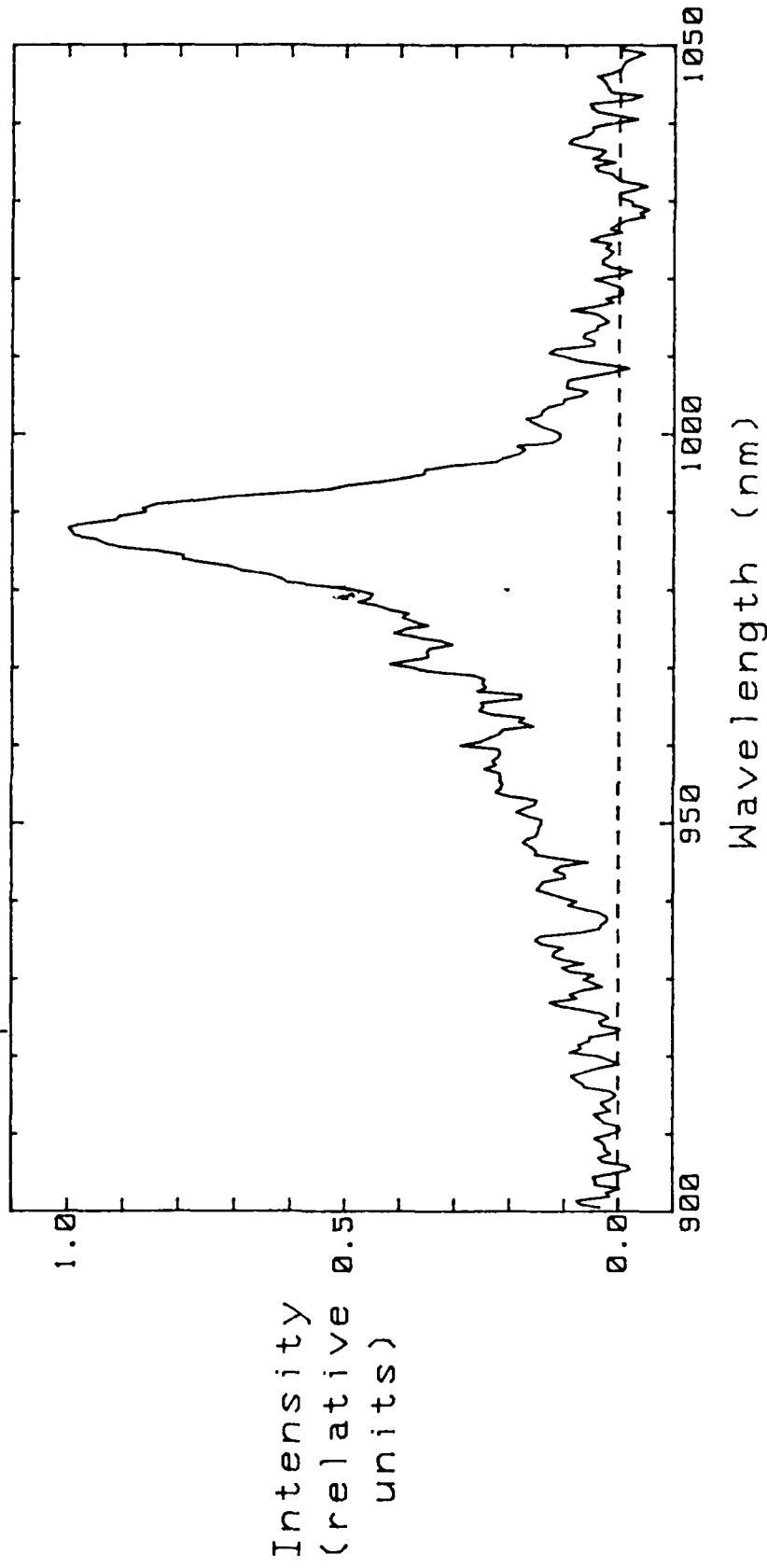
Figure 4(c). Photoluminescence Spectra of 50 periods of $In_{.15}Ga_{.85}As$/GaAs MQW on GaAs with Superlattice Cap and Buffer Layer
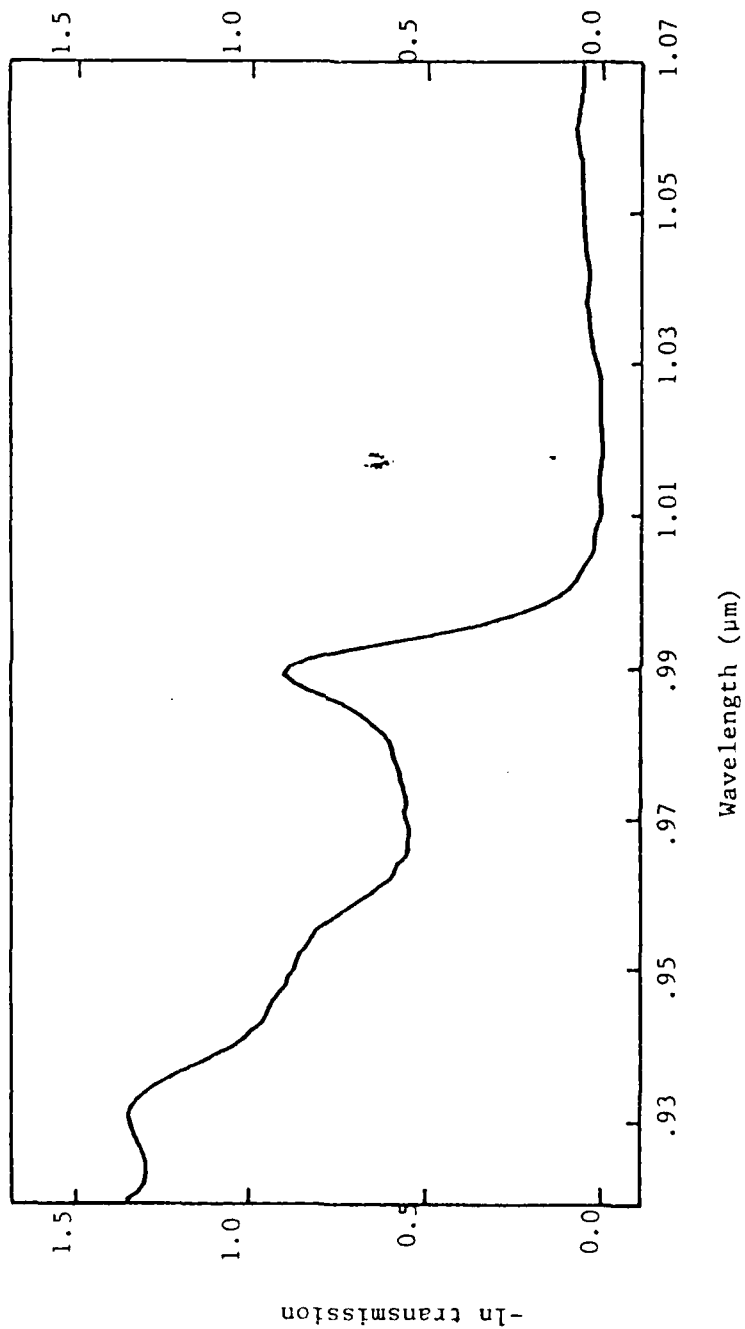
Figure 5a. Absorption spectrum of MBE-473: 80 100 Å In.15Ga.85As QW's with 100 Å GaAs barriers, grown on GaAs.
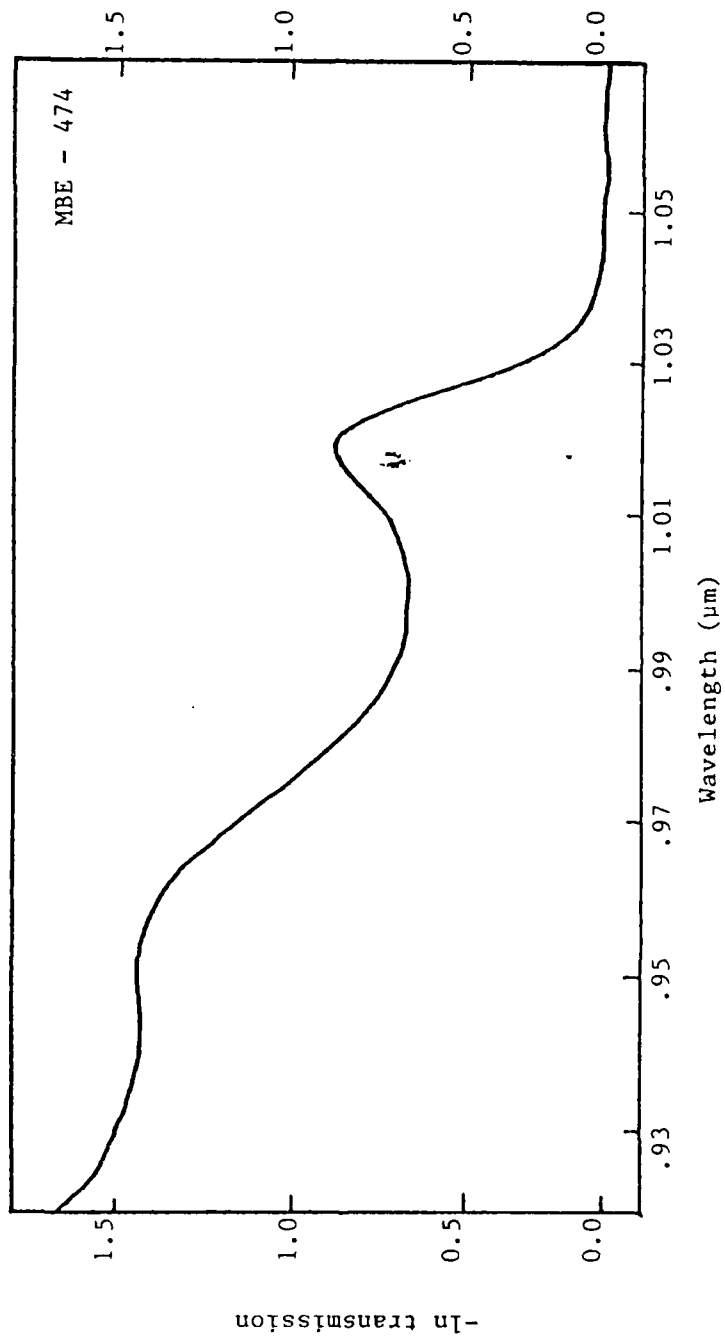
Figure 5b. Absorption spectrum of MBE-474: 80 100 Å In.19Ga.81As QW's with 100 Å GaAs barriers, grown on GaAs.
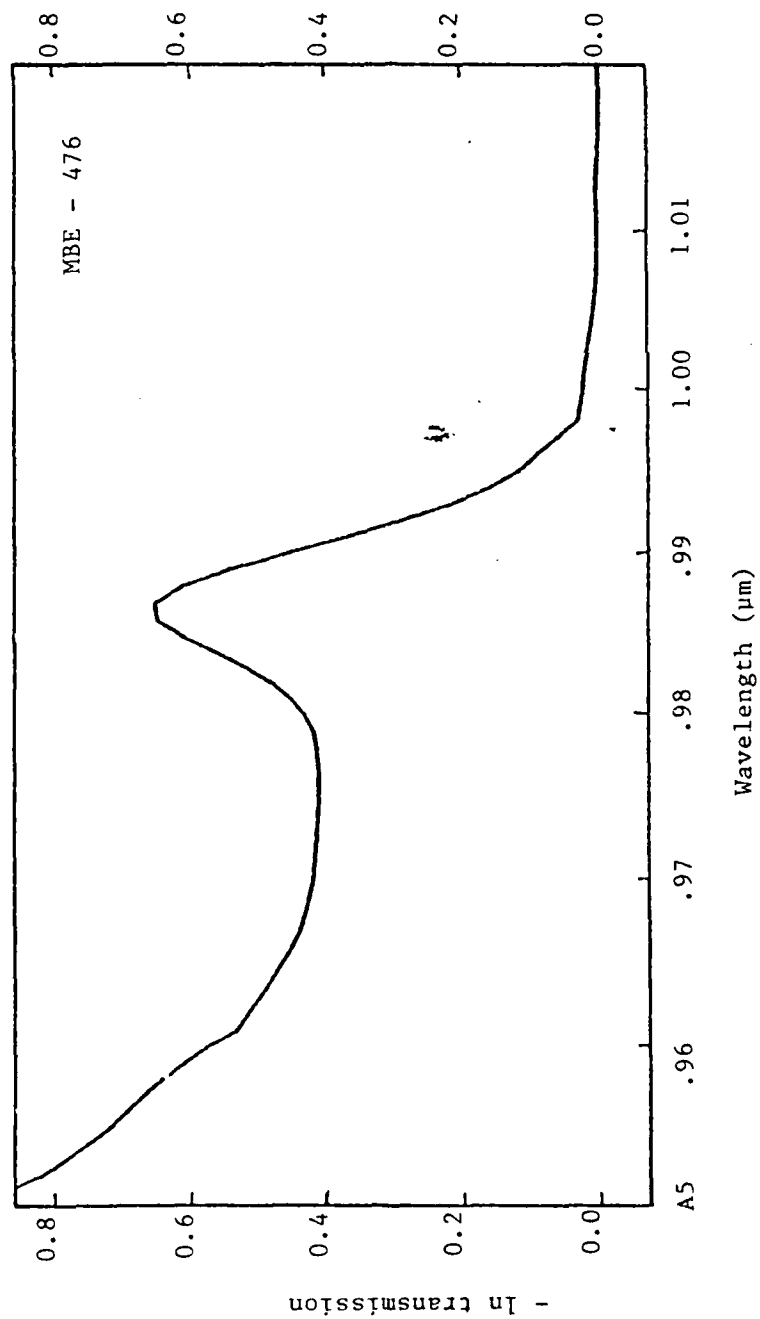
Figure 5c. Absorption spectrum of MBE-476: 50 100 Å In.15Ga.85As QW's with 100 Å GaAs barriers, grown on a strained buffer of 20 Å In.15Ga.85As and 20 Å GaAs layers.
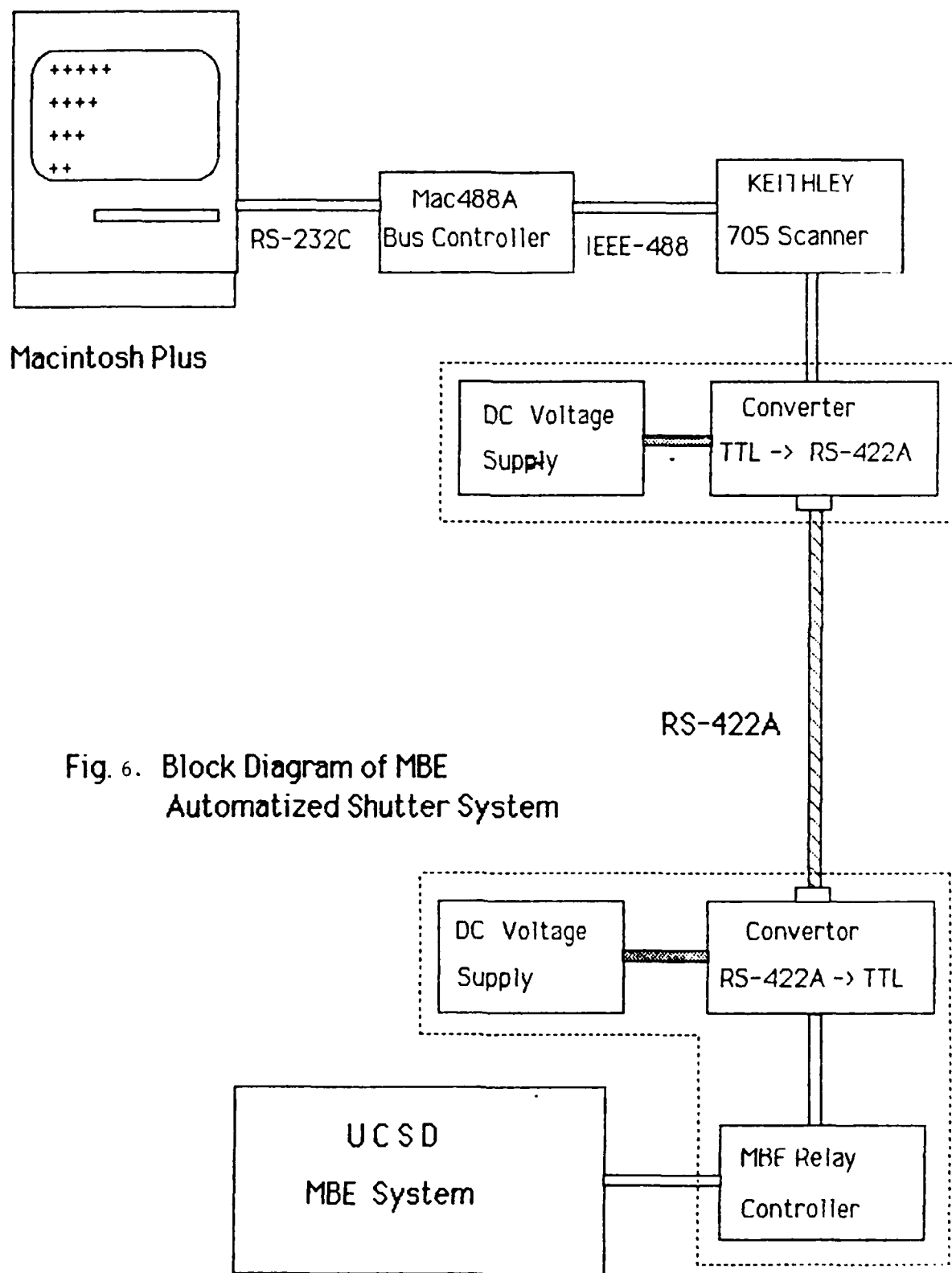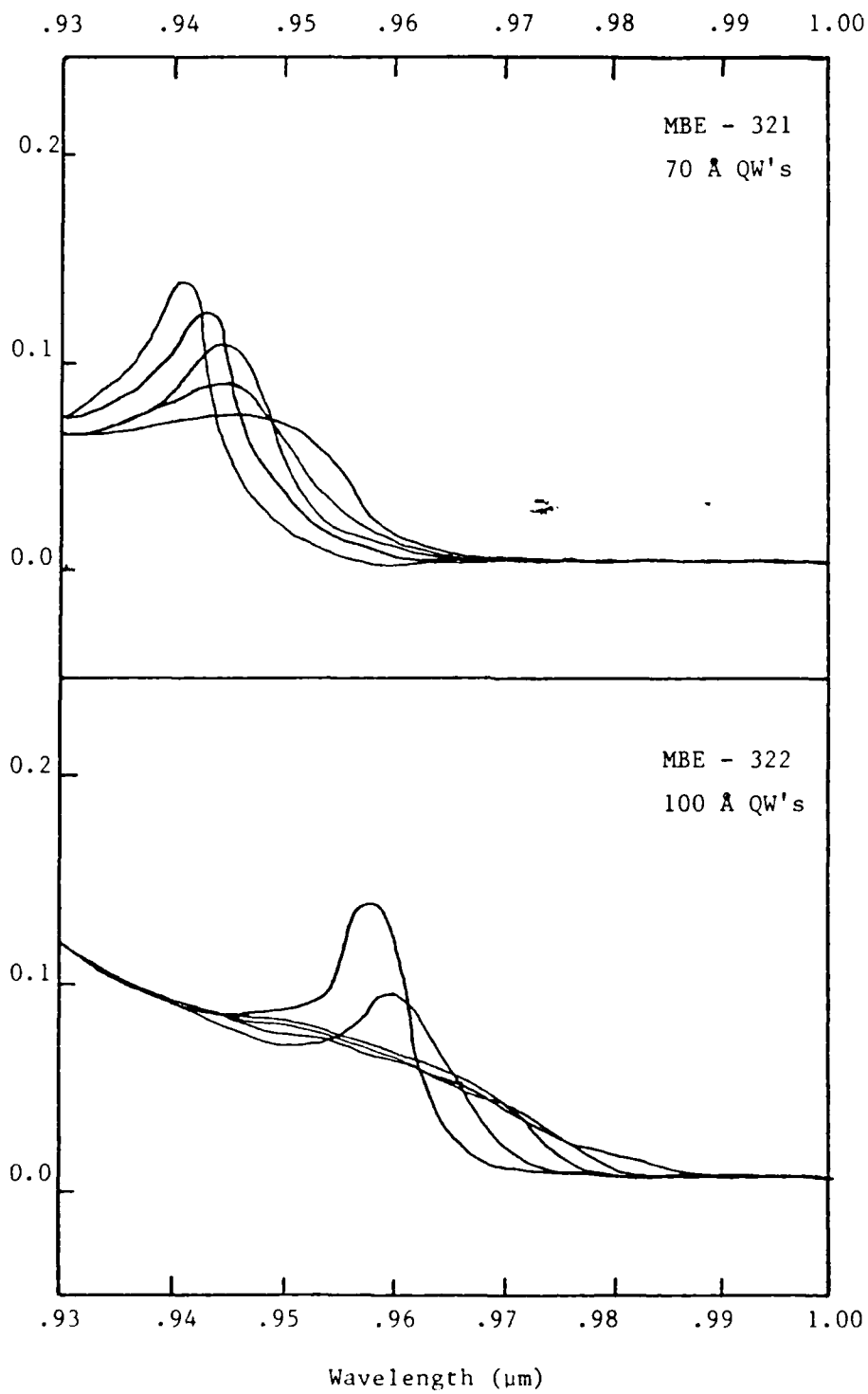
Fig. 6. Block Diagram of MBE
Automatized Shutter System

Figure 7. Electro-absorption in MBE-321 (70 Å QW's) and MBE-322 (100 Å QW's). Both have ten $In_{.12}Ga_{.88}As$ QW's and GaAs barriers.

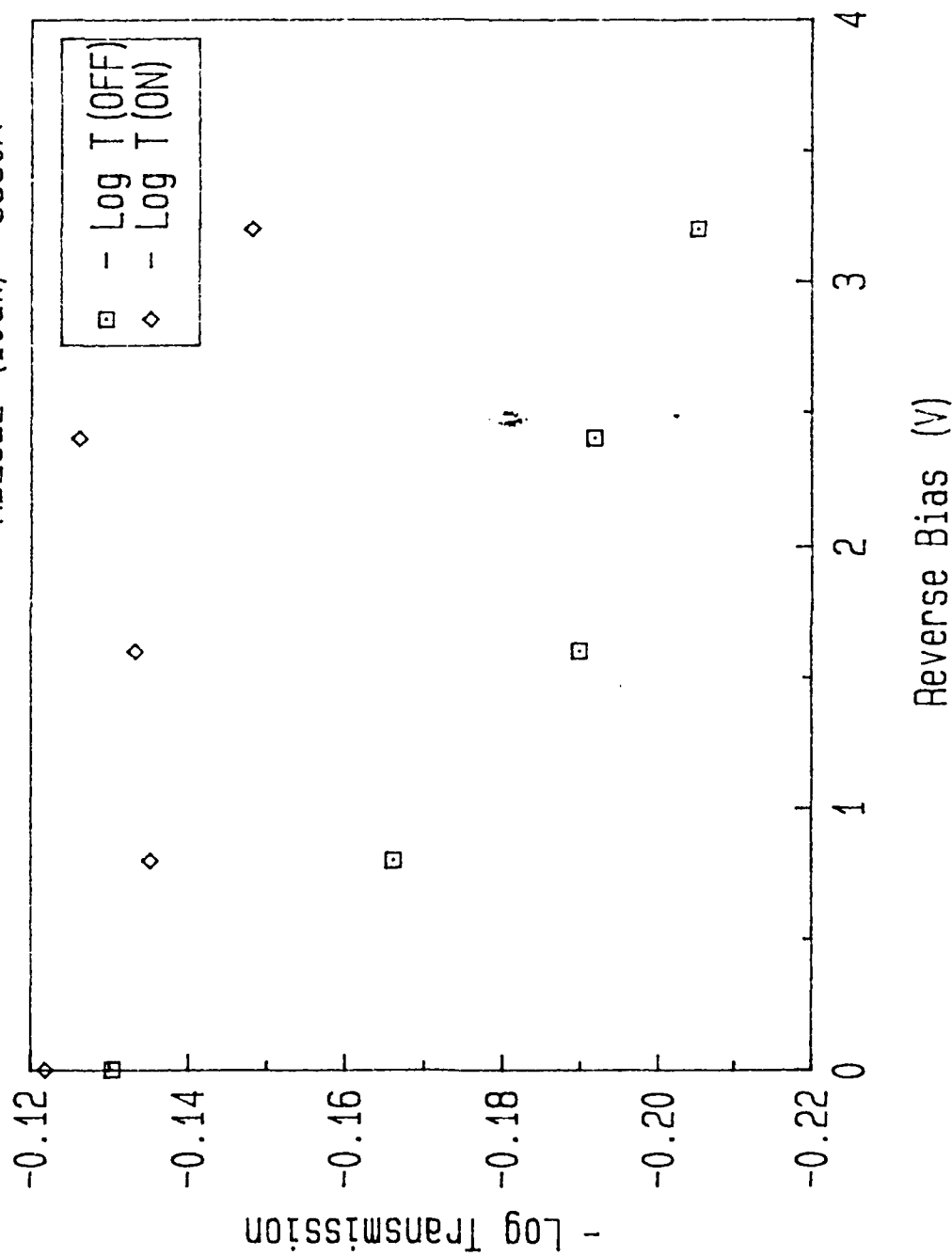Figure 8. Illustration of the Experiment for the Detector-Modulator Diode Pair.

Figure 9. The Transmission of the Detector-Modulator Diode Pair at λ = 9580 Å

– Log transmission vs Wavelength

MBE322 (10GW)

Legend:
- □ – Log T (VR=2.4V)
- ◇ – Log T (VR=0V)

Y-axis: – Log Transmission
Values: -0.13, -0.18, -0.23, -0.28

X-axis: Wavelength (nm)
Values: 950, 960, 970

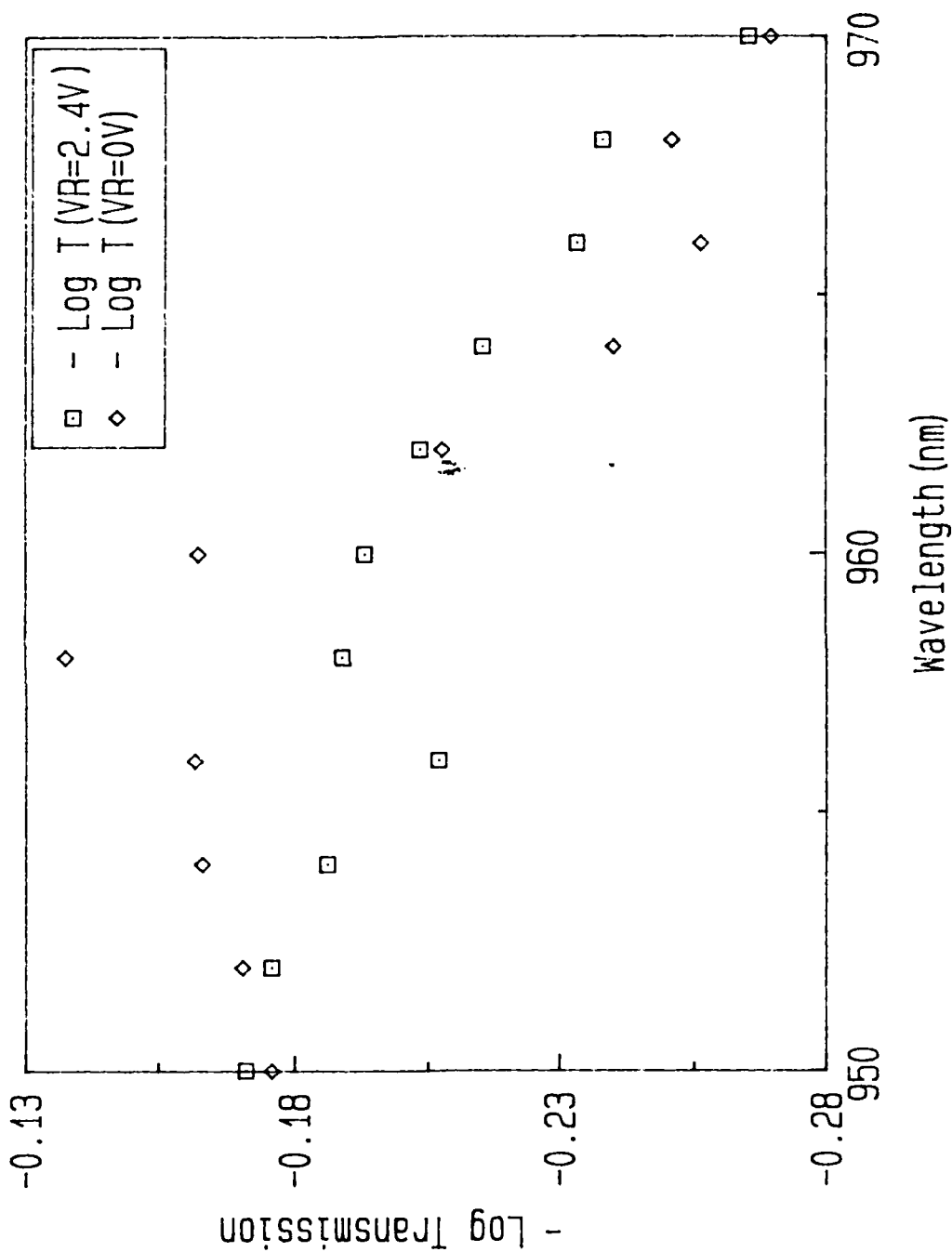Figure 10. The Transmission of the Detector-Modulator Diode Pair as a function of Wavelength.

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